

Chapter 19

Transmutation Scenarios after Closing Nuclear Power Plants

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Abstract With consideration of the phase-out option from nuclear power (NP) utilization in Japan, an accelerator-driven system (ADS) for Pu transmutation has been designed and scenario analysis performed. The ADS is designed based on the existing ADS design for MA transmutation, and the six-batch ADS was selected as a reference design for scenario analysis. In the scenario analysis, the once-through scenario of light water reactor (LWR) spent fuel is referred to as a conventional scenario with a LWR-MOX utilization scenario. As the transmutation scenario, three cases of transmuters that are only-FR, only-ADS, and both-FR+ADS are analyzed. The numbers of necessary transmuters are obtained as 15 to 32 units, and the necessary period for transmutation as 180–240 years. The benefit on repository by reduction of Pu and MA is reduction of repository area by a factor of five and of decay time of toxicity by one order of magnitude. The FR+ADS scenario would be a modest solution, although the ADS scenario is preferable if rapid transmutation is required.

Keywords ADS • Phase-out scenario • Scenario study • Transmutation

19.1 Introduction

After the Fukushima-Daiichi accident, Japan started a discussion of nuclear power (NP) utilization including a “phase-out” option in addition to the usual scenario of utilizing plutonium by deploying fast breeder reactors (FBRs). In the phase-out option, construction of new plants is limited and dependency on NP will be gradually reduced. One of the reasons supporting the phase-out scenario is an ambiguous prospect of conducting underground disposal of radioactive wastes. Increase of wastes can be limited or even stopped in the phase-out scenario, but spent fuels (SFs) containing plutonium (Pu) and minor actinides (MAs) will remain as a legacy of NP. “Direct disposal” to the underground of SFs confined in canisters is considered as a strong option to treat this legacy, but Pu and MAs that exist in the

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underground can be utilized for nuclear weapons and can cause public dose in the very far future over several tens of thousands of years. Instead of direct disposal, transmutation of Pu and MAs (TRU, trans-uranic) has been studied in many countries for the purpose of eliminating them from the waste.

Transmutation can be performed by a “transmuter” that is dedicated for transmutation with the lesser role of electricity generation. It contains a fast reactor (FR) and an accelerator-driven system (ADS), which are fast neutron systems with metal coolant. FRs have been mainly developed as breeder reactors but they act as a burner reactor in the phase-out scenario. The burner reactor has no blanket region for breeding, larger Pu content, and shorter operation-cycle length [1]. The ADS has been designed as an MA transmuter with a smaller amount of Pu but changes to a Pu transmuter in this scenario.

In the present study, an ADS for Pu transmutation (Pu-ADS) is designed by neutronics calculation based on the ADS for MA transmutation (MA-ADS). In the original design for MA transmutation, drop of criticality during depletion is very small, and a long operation cycle is achieved because MAs behave as fertile material. In the Pu-ADS, criticality decreases much more rapidly and design modification is necessary.

After the design of the Pu-ADS, a scenario study is performed by a nuclear material balance (NMB) code that was developed by the authors. The following items are revealed by the study: accumulation of TRU in the LWR SFs, necessary number of transmuters, reduction of TRU, reduction of repository footprint, and radiotoxicity by transmuters.

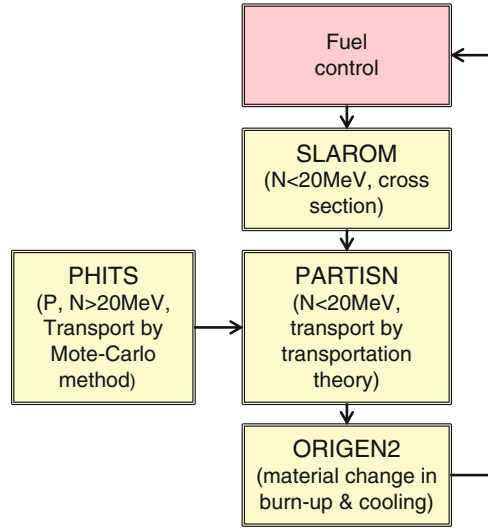
In Sect. 19.2, calculation methods for neutronics design and scenario code are introduced. Section 19.3 provides the neutronics design and resulting ADS. Section 19.4 discusses assumptions and results of the scenario study. The results are concluded in Sect. 19.5.

19.2 Methodology

19.2.1 Neutronics Calculation

Several codes were combined for ADS design (Fig. 19.1) containing proton transport, neutron transport, cross-section preparation, and depletion. The PHITS code [2] was used for transportation of protons and neutrons above the energy boundary of 20 MeV. Transportation of neutrons slowing down less than 20 MeV is interrupted, and position, direction, and energy are stored in a cutoff file. This file is processed as to be readable by the PARTISN code [3], which is a neutron transport code with multi-group theory. A 73-group cross section is prepared by SLAROM [4] code with the JENDL4.0 [5] nuclear data library. A 1-group micro-cross section is calculated by multiplying the 73-group cross section to the 73-group flux from PARTISN. One-group micro-cross section and total flux is used in the ORIGEN2

Fig. 19.1 Calculation codes



code [6] to obtain material change after depletion. The material composition from ORIGEN2 is processed by a fuel control program that simulates reprocessing and fuel fabrication with adjustment of MA content ratio.

19.2.2 Scenario Analysis

The NMB code [7] was employed for the scenario analysis. The code calculates material balance of 26 actinides (through Th to Cm, $T_{1/2} > \text{several days}$) in spent fuels with an accuracy comparable to the ORIGEN2 code. LWR, CANDU, gas-cooled reactor, several sodium-cooled FRs, and lead-bismuth-cooled ADS are available. Each reactor can be coupled with appropriate fuel such as UO_2 , MOX, ROX, Pu-nitride (PuN), and MA-nitride (MAN). Fission products are estimated by dividing them into several groups (iodine, rare gas, technetium and platinum group metals, strontium, cesium, and others). The number of waste packages and repository size are determined by temperature analysis based on several repository layouts. Potential radiotoxicity that is defined as dose by direct ingestion can be also estimated.

19.2.3 Transmutation Half-Life

In this section we define the effective transmutation rate and transmutation half-life that represent performance of a transmuter in the case of a phase-out scenario. A transmutation amount after an in-core period of T_{in} years is

$$w_{\text{tr}} = \frac{P T_{\text{in}} \cdot 3600 \cdot 24 \cdot 365 \cdot \varepsilon_o \cdot \bar{A}}{E_{\text{fiss}} N_A} . \quad (19.1)$$

Here, the effective transmutation rate, λ_{tr} , is transmuted amount divided by initial amount and time needed for transmutation including out-core period.

$$\lambda_{\text{tr}} = \frac{w_{\text{tr}}}{w_i} \frac{1}{T_i + T_o} = a \varepsilon_o \varepsilon_c h, \quad (19.2)$$

where,

$$a = \frac{3600 \cdot 24 \cdot 365 \cdot \bar{A}}{E_{\text{fiss}} N_A} \cong 3.8 \cdot 10^{-4} \cdot (\text{t/MW/year}) \quad (19.3)$$

Because a can be regarded as constant for Pu-transmuters, λ_{tr} is determined by operation efficiency, ε_o , cycle efficiency, ε_c , and specific heat, h . A time evolution of amount of heavy metal after introducing transmuters is expressed as

$$\frac{dw}{dt} = -\lambda_{\text{tr}} w, \quad w = w_0 e^{-\lambda_{\text{tr}} t}, \quad T_{\text{tr}} = \frac{\ln(2)}{\lambda_{\text{tr}}}, \quad (19.4)$$

where T_{tr} is a transmutation half-life. In the phase-out scenario, there is heavy metal of w_0 t when transmuters are employed in full scale. T_{tr} means a period needed to transmute half of w_0 in the case that the maximum number of transmuters are introduced. Another fact is that λ_{tr} and T_{tr} depend on two parameters relating to operation time efficiency and one fundamental core parameter, h . The thermal output of core affects a number of transmuters, but not transmutation behavior in the mass-flow analysis.

19.3 ADS Design for Pu Transmutation

19.3.1 Reference ADS (MA-ADS)

An ADS core dedicated for MA transmutation (MA-ADS) [8] bases the present design for Pu transmutation. As listed in Table 19.1, the MA-ADS is a medium-size core loaded with nitride fuel cooled by lead-bismuth eutectic (LBE). Nitride fuel is diluted by zirconium-nitride with a weight fraction of around 50 % (volume fraction around 65 %) that can be changed so that criticality becomes an appropriate level ($k_{\text{eff}}=0.97$). The ADS is operated for 600 effective full-power days (EFPDs) without any fuel reloading while the interval for maintenance of an accelerator can occur. In other words, the ADS is a one-batch core that implies large reactivity drop after depletion in the case of Pu transmutation. Because control rods for criticality are not equipped in the ADS, the drop must be supplemented by

Table 19.1 Parameters of minor actinides-accelerator-driven system (MA-ADS) [8]

Thermal power	800 MWt
Electricity generation	260 MWe
Proton energy	1.5 GeV
Transmutation rate	250 kg/300 EFPDs
Coolant	LBE
Upper limitation of k_{eff}	0.97
Operation period	600 EFPDs
Batch number	1
Fuel composition	(Pu+MA)N+ZrN
Pin outer diameter	7.65 mm
Pin pitch	11.48 mm

Table 19.2 MA composition fed to MA-ADS

	MA-ADS (%)
Np-237	49.5
Am-241	32.2
Am-243	13.4
Cm-244	4.4
Cm-245	0.4

Table 19.3 Pu composition fed to Pu-ADS and Pu+U-ADS

ADS case	Pu (%)	Pu+U (%)
U-235	–	0.1
U-238	–	49.9
Pu-238	2.4	1.2
Pu-239	54.5	27.2
Pu-240	24.2	12.1
Pu-241	11.9	6.0
Pu-242	7.0	3.5

increasing proton beam current. Fortunately, MAs are fertile material that becomes fissile after capturing one neutron, and the drop is very small, as shown in the following section. Table 19.3 provides weight composition of MA fed to MA-ADS. Figure 19.2 illustrates the R-Z model for calculation.

19.3.2 Assumption of Pu Feed

Two cases of Pu feed were assumed in the present design for Pu transmutation: Pu-ADS, to which only Pu is provided from reprocessing process of LWR SF, and Pu+U-ADS, to which Pu accompanied by U with 50 % weight ratio is provided from the process. Treatment of pure Pu raises proliferation concern in a country without nuclear weapons, and the reprocessing plant is designed to add depleted

Fig. 19.2 R-Z model of
accelerator-driven system
(ADS)

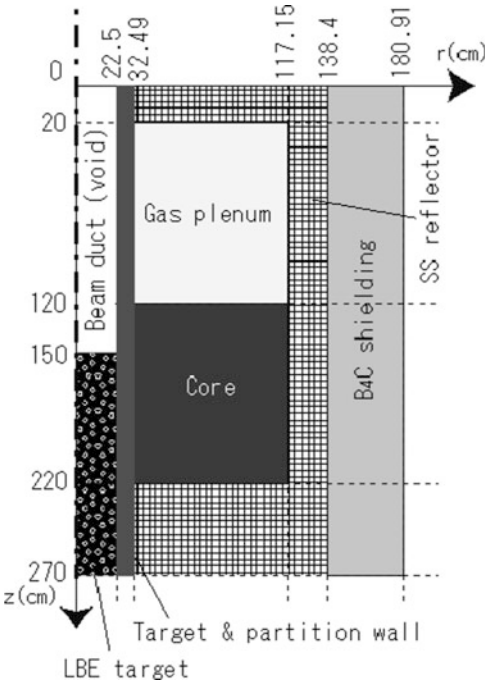


Table 19.4 Efficiencies
of ADSs

ADS case	MA (Ref.)	Pu	Pu+U
T_i (years)	2	1	2
T_o (years)	3	3	3
ϵ_o (%)	82.1	82.1	82.1
ϵ_c (%)	40.0	25.0	40.0

U to Pu just after separation. Addition of ^{238}U results in ^{239}Pu production and generally is undesirable for Pu transmutation. Table 19.3 lists two compositions. Other conditions are similar to the MA-ADS.

19.3.3 Result of One-Batch Core

The reference ADS for MA transmutation is designed with a one-batch core, which means that all the fuel is loaded and unloaded simultaneously. At first, this one-batch design was adopted to Pu transmuters. Table 19.4 lists the in-core and out-core time with operation efficiency. Out-core time of the ADSs is 3 years, which allows decay of ^{244}Cm . In-core time of the reference MA-ADS is 2 years, although that of Pu-ADS is reduced to 1 year because the decrease of criticality is

Table 19.5 ADS inventories and transmutation half-life for one-batch design (equilibrium core)

ADS case		MA (Ref.)	Pu	Pu+U
Volume fraction of inert matrix (%)		69.8	87.1	68.1
Core inventory at BOC (t)	U	0.19	0.02	2.62
	Pu	1.83	1.84	1.88
	MA	2.37	0.25	0.18
Core inventory at EOC (t)	U	0.18	0.02	2.39
	Pu	1.79	1.60	1.63
	MA	1.92	0.25	0.18
Transmutation, BOC-EOC (t)	U	0.00	0.00	0.23
	Pu	0.04	0.24	0.26
	MA	0.45	0.00	0.00
Specific heat, h (MW/tHM)		182	380	171
λ_{tr} (/year)		2.28E-02	2.96E-02	2.14E-02
T_{tr} (year)		30.5	23.4	32.5

too rapid for this ADS. The operation efficiency, ϵ_o , is 82.1 % assuming 300 days operation annually.

Design and transmutation performance are summarized in Table 19.5. Volume fraction of the inert matrix, ZrN, of the MA-ADS core is 69.8 %, adjusted so that k -effective at the beginning of the cycle (BOC) of the equilibrium core becomes 0.97. The equilibrium core is obtained after calculating ten cycles of burning, cooling, and recycling. Volume fraction of the Pu-ADS is more and that of the Pu+U-ADS is almost the same. The inventory at BOC of the heavy metal in Table 19.5 is proportional to a one-volume fraction of ZrN. An interesting observation is that the amounts of Pu at BOC are equal among three ADSs, which means U and MA contribute very little to the criticality before depletion. However, impacts on the criticality drop after depletion is significant (Fig. 19.3). k_{eff} drop of the MA-ADS is as small as 1.5 %dk, although others lose 14 %dk even at the equilibrium cycle around 6,000 days, which means MA is a better fertile than ^{238}U . The Pu-ADS has a steeper decrease than Pu+U-ADS because of the absence of ^{238}U . The huge drop of the Pu- and Pu+U-ADS is not acceptable in the current design of accelerator and target for the MA-ADS; the acceptable drop is about 3 %dk in the MA-ADS.

The effective transmutation rate and transmutation half-life are listed at the bottom of Table 19.5. The half-life of the Pu-ADS is shortest because its specific heat is twofold larger than others although its cycle efficiency, ϵ_c , is much smaller than others.

19.3.4 Result of six-Batch Core

In the one-batch design in the previous section, k_{eff} drop of Pu ADSs is 14 %dk, which is too large to be compensated by burnable poison or control rods. As the first step of design improvement, a multi-batch design is introduced. Theoretically, an

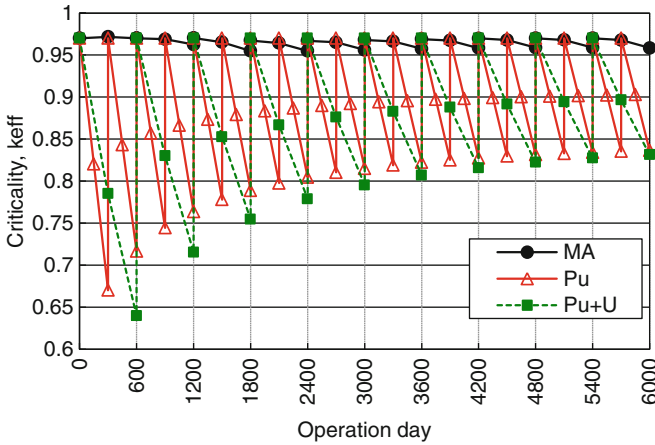


Fig. 19.3 Time evolution of criticality for one-batch design

N-batch core can reduce k_{eff} drop by $1/N$, that is, a drop of 14 %dk can be reduced to 2.3 %dk by six-batch design. Figure 19.4 illustrates the criticality change with an expansion for operation date of 0–1,200 days. The criticality drop for the early operation date is larger than the limit of 3 %dk, that is, 0.94 of k_{eff} at end of burn-up; the drop decreases in the equilibrium cycle. The maximum drop is 5 %dk for Pu-ADS and 6.5 %dk for Pu+U ADS, which can be compensated by control rods or burnable poison or mitigated by shorter operation in the early cycle in future improvements. The drop in the equilibrium cycle is approximately 2 %dk, which is comparable to that of the reference MA-ADS.

Volume fractions and inventories are listed in Table 19.6. Six-batch cores generally require more inventory than a one-batch core because an averaged k_{eff} during operation of multi-batch cores is higher than that of the one-batch core. Transmutation amounts of Pu- and Pu+U-ADSs are much smaller than that of the MA-ADS because the operation period is, respectively, only 50 and 100 days.

To evaluate transmutation half-life, operation and cycle efficiencies must be determined. The short operation period of 50 or 100 days implies frequent fuel exchange and low operation efficiency. There are two kinds of interval: fuel exchange and plant maintenance. We assumed that fuel exchange of a 1/6 core requires 15, 30, or 60 days for the Pu- and Pu+U-ADS and that plant maintenance including accelerator needs 60 days. Because fuel exchange for 15 days is very short, considering shutdown and startup of the ADS plant is included, tentative storage inside a core vessel should be applied for such a short interval. In the case of Pu-ADS, the 50-day operation and 15-, 30-, or 60-day interval are repeated five times, then 50-day operation and 60-day maintenance are done. In the case of Pu+U-ADS, 100-day operation and 15-, 30-, or 60-day interval are repeated two times, then 100-day operation and 60-day maintenance are done. The total operation period before a long plant maintenance of 60 days in both ADSs is 300 days.

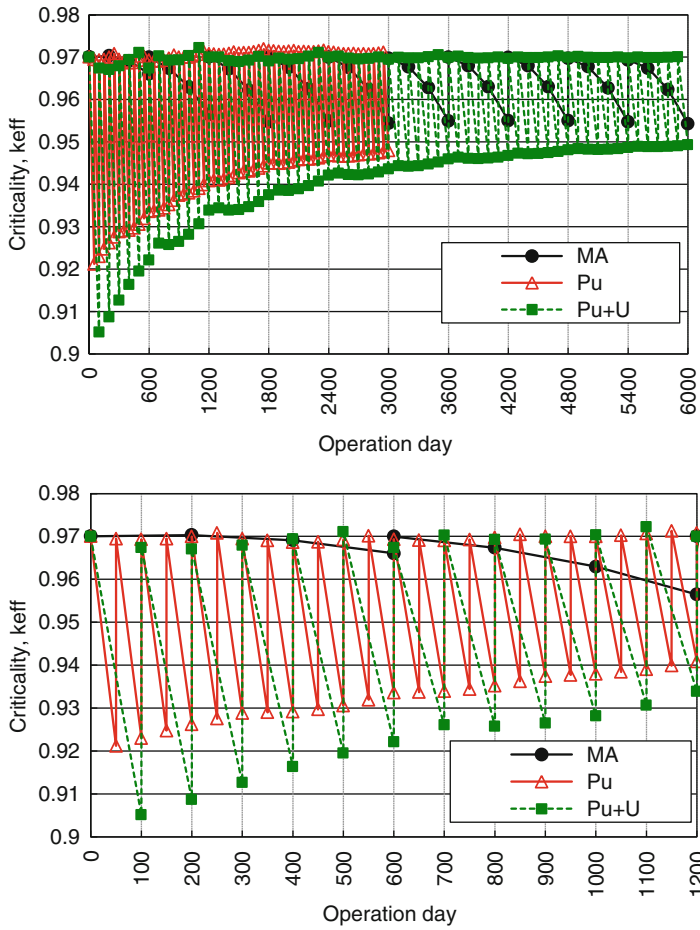


Fig. 19.4 Time evolution of criticality for six-batch design (*upper* = all operation, *lower* = expansion)

Table 19.6 ADS inventories for six-batch design (equilibrium core)

ADS case		MA (Ref., 1-batch)	Pu	Pu+U
Volume fraction of inert matrix (%)		69.8	85.4	62.5
Core inventory at BOC (t)	U	0.19	0.01	3.05
	Pu	1.83	1.84	2.04
	MA	2.37	0.19	0.20
Core inventory at EOC (t)	U	0.18	0.01	3.01
	Pu	1.79	1.80	2.00
	MA	1.92	0.19	0.20
Transmutation, BOC-EOC (t)	U	0.00	0.000	0.037
	Pu	0.04	0.041	0.043
	MA	0.45	0.000	0.000
Specific heat, h (MW/tHM)		182	393	151

Table 19.7 Assumption on maintenance schedule versus transmutation half-life for six-batch design (equilibrium core)

ADS case	MA	Pu			Pu + U		
Interval case	2×65 days	15×5 $+ 60 \times 1$	30×5 $+ 60 \times 1$	60×5 $+ 60 \times 1$	15×4 $+ 60 \times 2$	30×4 $+ 60 \times 2$	60×4 $+ 60 \times 2$
Batch	1	6	6	6	6	6	6
Operation (days)	600 ^a	50	50	50	100	100	100
Short interval (days) ^b		15	30	60	15	30	60
Long interval (days) ^c	130 ^a	60	60	60	60	60	60
ε_o (%)	82	69	59	45	77	71	63
In-core period (years)	2	1.19	1.40	1.81	2.01	2.22	2.63
Out-core period (years)	3	3	3	3	3	3	3
E_c (%)	40	28	32	38	40	43	47
$E_o * \varepsilon_c$ (%)	33	20	19	17	31	30	29
h (MW/tHM)	182	393	393	393	151	151	151
λ_{tr} (/years)	2.28E-02	2.93E-02	2.79E-02	2.55E-02	1.78E-02	1.75E-02	1.68E-02
Ttr (years)	30.5	23.7	24.8	27.2	39.0	39.7	41.3

^aTwo times of operation for 300 days and long interval for 65 days, in real

^bMaintenance for fuel reloading of 1/6 core; short interval occurs five times for Pu-ADS and two times for Pu+U-ADS between long intervals

^cMaintenance for accelerator and plant

Based on the foregoing assumptions, operation efficiency and cycle efficiency are determined as listed in Table 19.7, with specific heat and resulting transmutation half-life. Operation efficiency multiplied by cycle efficiency of the Pu-ADS is the poorest, but the transmutation half-life is the shortest because of the high specific heat. In the present study, a 30-day interval for fuel exchange is adopted as a nominal case. The transmutation half-life of the Pu-ADS is 24.8 years in the nominal case, which is applied to scenario analysis.

Another observation is that the impact of the out-core period on cycle efficiency is significant. The out-core period is presumed considering the half-life of ^{242}Cm of 126.8 days. If a shorter out-core period is accomplished by corresponding design of the reprocessing and fabrication plant, cycle efficiency and resulted transmutation half-life can be improved. Table 19.8 shows comparison of a 3-year and 1-year out-core period. An impact on the transmutation half-life of the Pu-ADS is a factor of around 2, and the transmutation half-life becomes as short as 13.5 years. Although 3 years of out-core period is applied as the nominal case, a shorter out-core period should be pursued in future study.

Table 19.8 Impact of out-core period on transmutation half-life

ADS case	MA	Pu	Pu+U
Interval case	2×65 days	$30 \times 5 + 60 \times 1$	$30 \times 4 + 60 \times 2$
In-core period (years)	2.0	1.4	30.0
Out-core period (years)	3.0	3.0	3.0
Ttr (years)	30.4	24.8	39.7
Out-core period (years)	1.0	1.0	1.0
Ttr (years)	18.3	13.5	24.5

19.4 Scenario Analysis

Based on the ADS design in Sect. 19.3 and FR design in Wakabayashi et al. [1], the impact of introducing transmutation is evaluated by mass-flow analysis. Table 19.9 lists analyzed scenarios in which two conventional scenarios and three transmutations are included. In the conventional once-through scenario identified as “LWR-OT,” Pu and MA exist in spent fuel and are directly disposed of in an underground repository. The second conventional scenario identified as “LWR-PuT” is Pu utilization in a LWR. The spent uranium fuels from an LWR are reprocessed, and, separated Pu is fabricated as MOX and burned in the LWR. Spent MOX fuel is directly disposed.

In the FR scenario, both Pu and MA are mixed or co-extracted and transmuted in FR without any limit of MA content in the fuel. In the ADS scenario, Pu is transmuted in the present design (Pu-ADS) and MA are transmuted in the reference ADS (MA-ADS). In the FR+ADS scenario, MA content in FR is limited to less than 5 % and the remaining MA are transmuted in the ADS.

Characteristics of transmutation systems are listed in Table 19.10. FR has a twice larger thermal output than ADSs, although the specific heat is smaller. Therefore, initial inventory involving fuels in the core and in the fuel cycle of FR is much larger than Pu-ADS even if uranium is excluded; thus, the number of FR that can be introduced is limited. As a result, the transmutation half-life of FR is longer than ADSs by a factor of two.

19.4.1 Result of LWR-OT

Figure 19.5 illustrates a result of the LWR-OT scenario where time evolution of electricity generation, Pu inventory, and MA inventory are shown. The peak of 50 GWe appears in 2010 and decreases because of the Fukushima accident and closure after 40-year operations. All LWRs will be shut down in 2055. The Rokkasho reprocessing plant (RRP) will not be operated, but 7,100 tHM spent fuel has been reprocessed, mainly overseas. The year of reprocessing is not clear

Table 19.9 Scenarios

Scenario		Pu	MA
Conventional	LWR-OT (once-through)	Waste	Waste
	LWR-PuT	LWR	Waste
Transmutation	FR (Pu+MA15 %)	FR	FR
	ADS (TRU)	ADS	ADS
	FR (Pu+MA5 %)+ADS (TRU)	Mainly, FR	Mainly, ADS

Table 19.10 Characteristics of transmutation systems

		FR	Pu-ADS	MA-ADS
Power (thermal/electric)	GWe	1.6/0.6	0.8/0.264	
Pu ratio (in/out)	%	37.5/45	~100	~35
MA/HM ratio	%	<5	—	~65
Batch number		4	6	1
Operation period	Day	183	50	600
Operation efficiency	%	84 %	59 %	82 %
In-core period	Year	2.39	1.40	2.00
Out-core period	Year	3.00	3.00	3.00
Cycle efficiency	%	44 %	32 %	40 %
Burn-up	GWd/tHM	58.56	120	108
Specific heat	MW/tHM	80	400	180
λ_{tr}	/year	1.13E-02	2.84E-02	2.25E-02
T_{tr}	Years	61.3	24.4	30.9
Initial inventory ^a	t/unit	45.1	6.3	11.1

^aInitial inventory involves fuel in core and in fuel cycle (cooling, reprocessing, and fabrication)

but assumed to be in the 1990s. A small amount of MOX fuel from this reprocessing will be utilized in LWRs.

Pu inventory mainly exists in UO₂-SF. “Pu” in the figure is not “separated” Pu, but Pu in MOX fresh fuel in this scenario. The total of plutonium is 350 t that is gradually disposed of to a repository from 2043 until 2105. The trend of MA inventory is almost the same, but it continues to increase after 2040 because ²⁴¹Pu becomes ²⁴¹Am with a half-life of 14.35 years.

19.4.2 Result of LWR-PuT

In MOX scenarios, the Rokkasho reprocessing plant (RRP) will be operated with annual capacity of 800 t and a MOX fabrication plant also (Fig. 19.6). The total amount of UO₂-SF reprocessed is 34,500 tHM, slightly larger than the planned amount of 32,000 tHM. Thus, the present analysis assumes an extension of the RRP by several years. The MOX loading to a usual LWR is limited to 30 %, although the

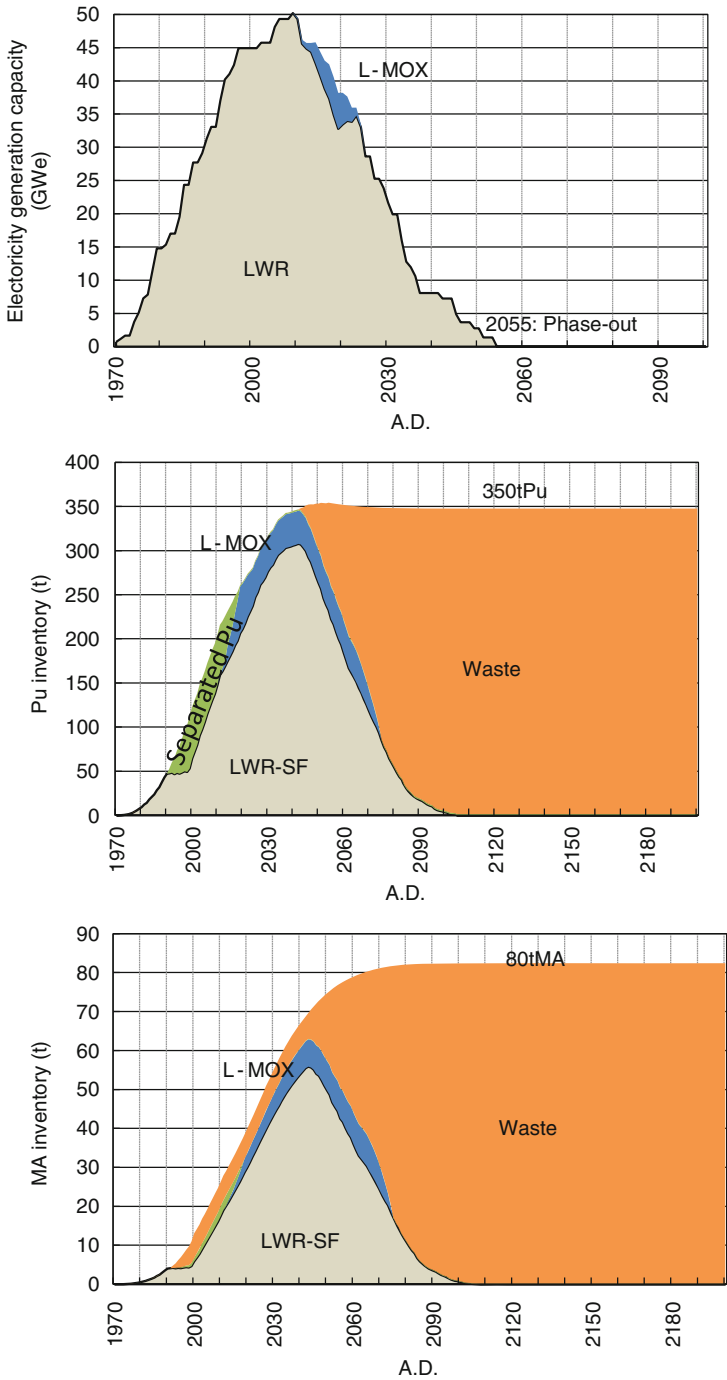


Fig. 19.5 Result of LWR-OT scenario

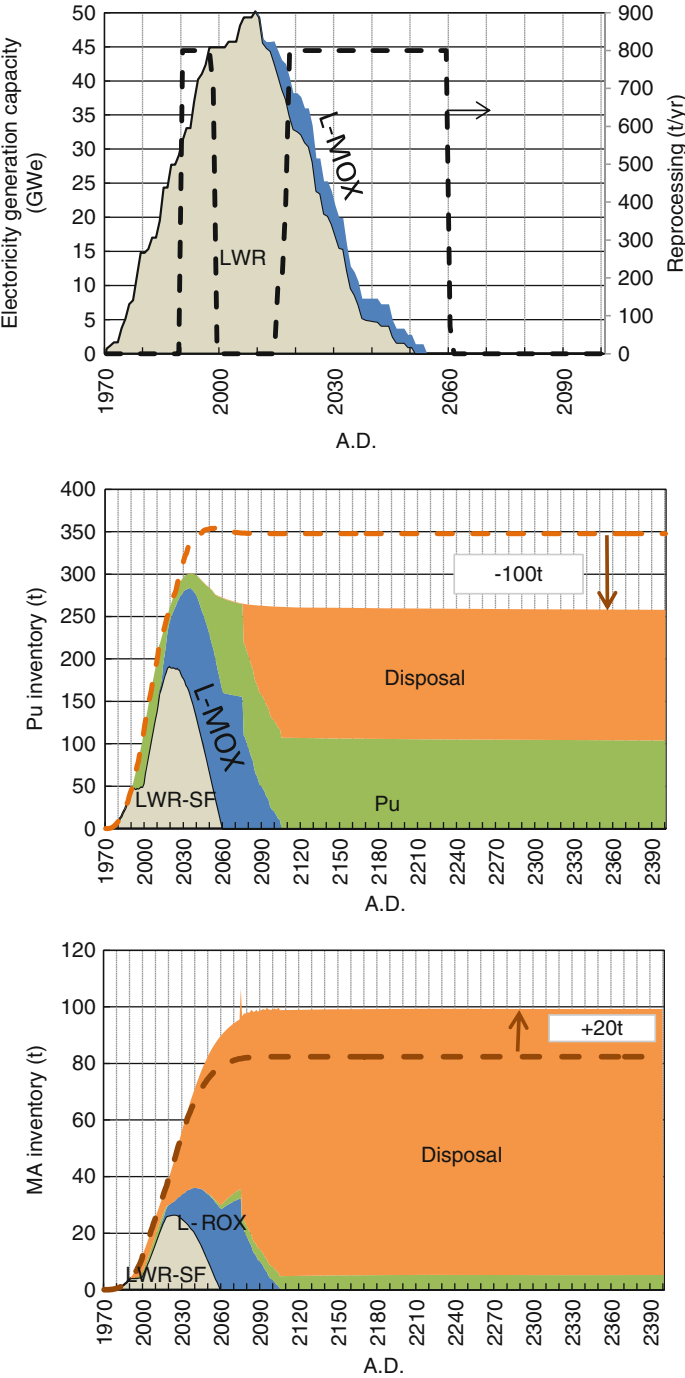


Fig. 19.6 Result of LWR-PuT scenario

Ohma full-MOX reactor starting in 2014 in this analysis can be operated only by MOX fuel. Because the RRP is operated after all LWRs are closed, part of the separated Pu cannot be burned. The total amount of Pu is reduced to 250 t, but that of MA is increased to 100 t.

19.4.3 Result of FR

In the FR scenario as well as other transmutation scenarios, Pu from the RRP is at first fabricated as LWR-MOX fuel and burned in LWR. Pu is co-extracted with same content of U in the current RRP, although MA is vitrified as waste. MA partitioning is assumed to be introduced in 2025 and stored until 2045. In 2045, before introduction of transmuters in 2050, reprocessing of LWR-MOX spent fuel will begin and provide Pu to the transmuters.

FRs are to be introduced in 2050 when 250 t plutonium and 100 t MA remains. MA of 20 t is vitrified by the RRP before 2025 and is not available for transmutation. Available TRU is 330 t. The required TRU to introduce an FR is approximately 25 t, if we assume 41 % of Pu content and 15 % of MA content and employ 45.1 t from Table 19.10. Theoretically, 14 ($=350/25$) FRs can be introduced in 2050, but only 8 can be deployed in practice because the plant life of an FR is assumed to be 60 years and sufficient TRU must be kept until 2110. Available TRU gradually decreases to 200 t in 2110 by transmutation. After 2110, FRs are replaced and reduced to 3 units corresponding to available TRU of 200 t that decreases to 130 t in 2170. Then, 2 FRs from 2170 to 2230 and 2 FRs from 2230 to 2290 will be deployed. After four generations of transmutation, the amounts of Pu and MA are reduced to 40 and 30 t, respectively.

MA content of FR is as high as 15 % (Fig. 19.7), which is above the design limit of 5 % in Wakabayashi et al. [1]. In the usual design of FBRs, MA accumulation is mitigated by a supply of fresh Pu from the blanket. Moreover, high Pu content of FR burner contributes to high MA content. High MA content generally causes deterioration of safety parameters (beta, Doppler coefficient, void reactivity) and difficulty in a reprocessing and fabrication plant.

19.4.4 Result of ADS

In the ADS scenario, transmuter is changed from FR to ADS. ADS can accept both Pu and MA; distribution is shown in Fig. 19.8. In 2050, 22 ADSs are to be introduced, corresponding to 140 t available TRU. Then, 7 and 3 ADSs are operated respectively from 2110 to 2170 and 2170 to 2230. After three generations, Pu and MA are reduced to 10 t and 3 t, respectively, excluding 16 t MA in vitrified waste.

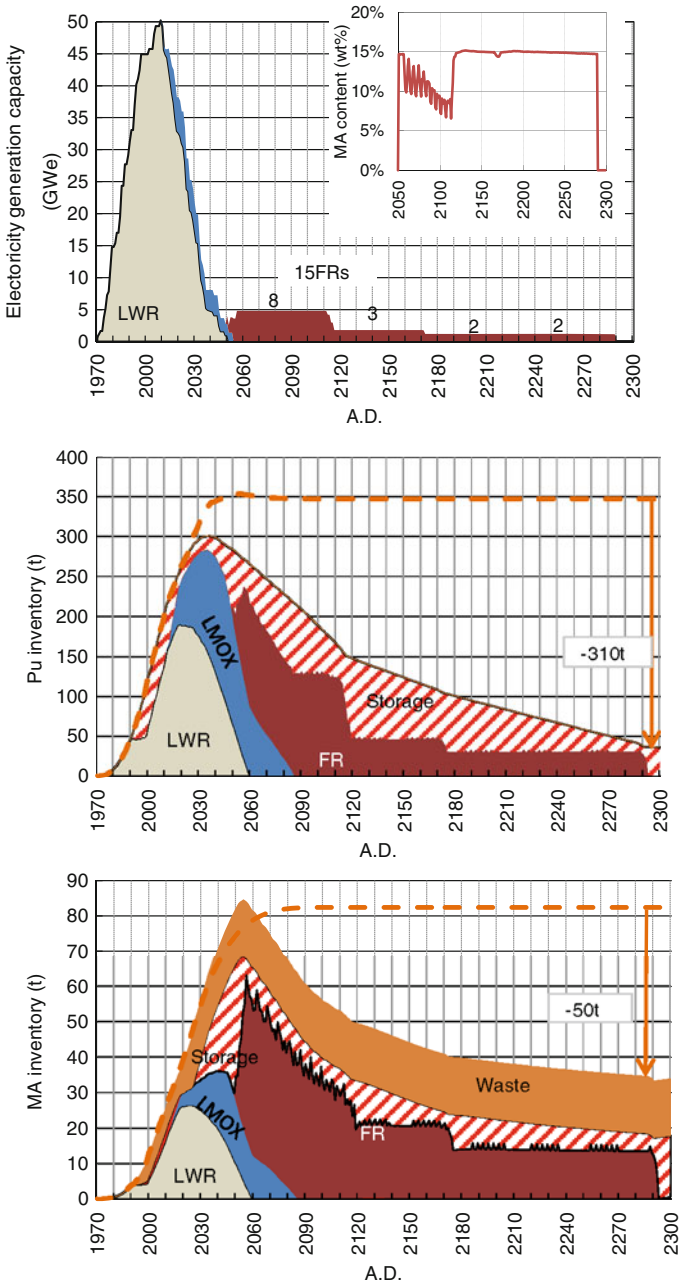


Fig. 19.7 Result of fast reactor (FR) scenario

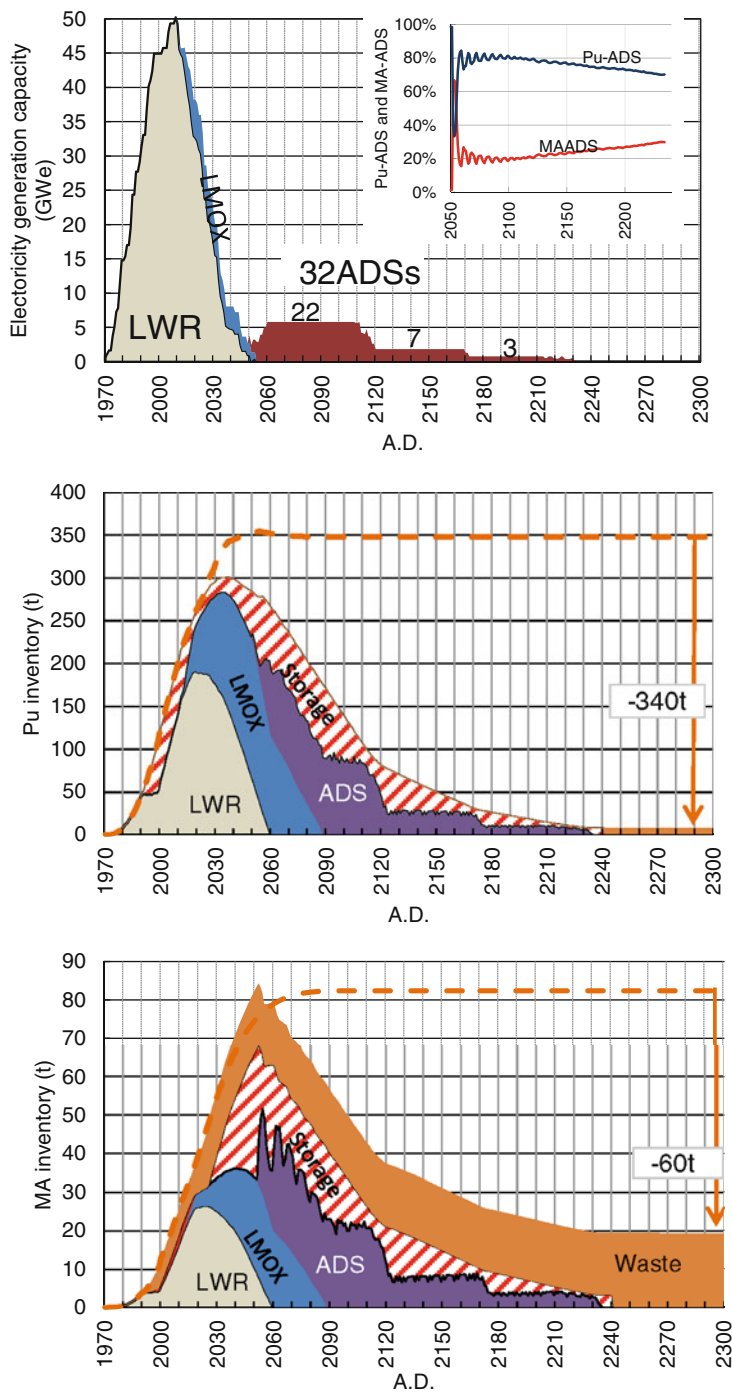


Fig. 19.8 Result of ADS scenario

19.4.5 Result of FR+ADS

In the FR+ADS scenario, MA content in FR is limited below 5 % with respect to design limit and the remaining MA is transmuted in the ADS. In the first generation of transmutation from 2050 to 2110, six FRs and three ADSs are deployed, then three FRs and two ADSs in the second generation, and two FRs and one ADS in the third generation are built (Fig. 19.9). In the fourth generation, only ADS is utilized as to reduce TRU rapidly. The total amount of Pu and MA is reduced to 20 and 10 t, respectively, excepting MA in vitrified waste.

19.4.6 Impact on the Repository

One of the impacts on the repository by transmutation is reduction of potential radiotoxicity, which is defined as total ingestion dose of the waste. Because waste is isolated from the public in the underground in reality, such direct ingestion never occurs and it is considered to be hypothetical, but it can represent the potential danger of waste. This toxicity of waste can be compared to that of uranium ore consumed for electricity generation causing radioactive wastes. Figure 19.10 illustrates those toxicities corresponding to whole operation of LWRs and transmuters. Consumed natural uranium is 370,000 t.

When wastes are generated, the toxicity becomes higher than corresponding uranium ore by three orders of magnitude. Fission products such as Sr and Cs are dominant in the early several hundreds of years, although actinides contribute to toxicity after that. Toxicity in the LWR-OT scenario decays to the level of uranium ore after 100,000 years. By reducing Pu in the LWR-PuT scenario, the decay time becomes shorter, to 70,000 years. In the transmutation scenarios, shortening of decay time depends on the remaining amount of TRU. The decay time is about 10,000 years in the ADS scenario in which the remaining TRU is approximately 30 t, including vitrified wastes. In comparison between the LWR-OT scenario and the ADS scenario, the amount of TRU is reduced by one order of magnitude, so toxicity is also reduced by same order. If MA in the vitrified wastes is retrievable, the amount of TRU will be reduced to around 10 t, which implies toxicity is reduced to 1/30 and the decay time is around 2,000 years. Thus, the impact on toxicity by transmutation is significantly affected by MA in the vitrified wastes. Early introduction of MA partitioning to the RRP and R&D for retrievability from the glass wastes is of importance in this aspect.

Another impact on the repository is reduction of repository size by partitioning and transmutation of heat-generating nuclides in the wastes. Repository size is represented by a repository footprint, which is defined as an area devoted for waste excluding aisles, ducts, utility area, surface facility, and other.

In the LWR-OT scenario, the footprint corresponding to 45,000 t spent fuel reaches almost 4 km², which is double the typical repository design for the glass

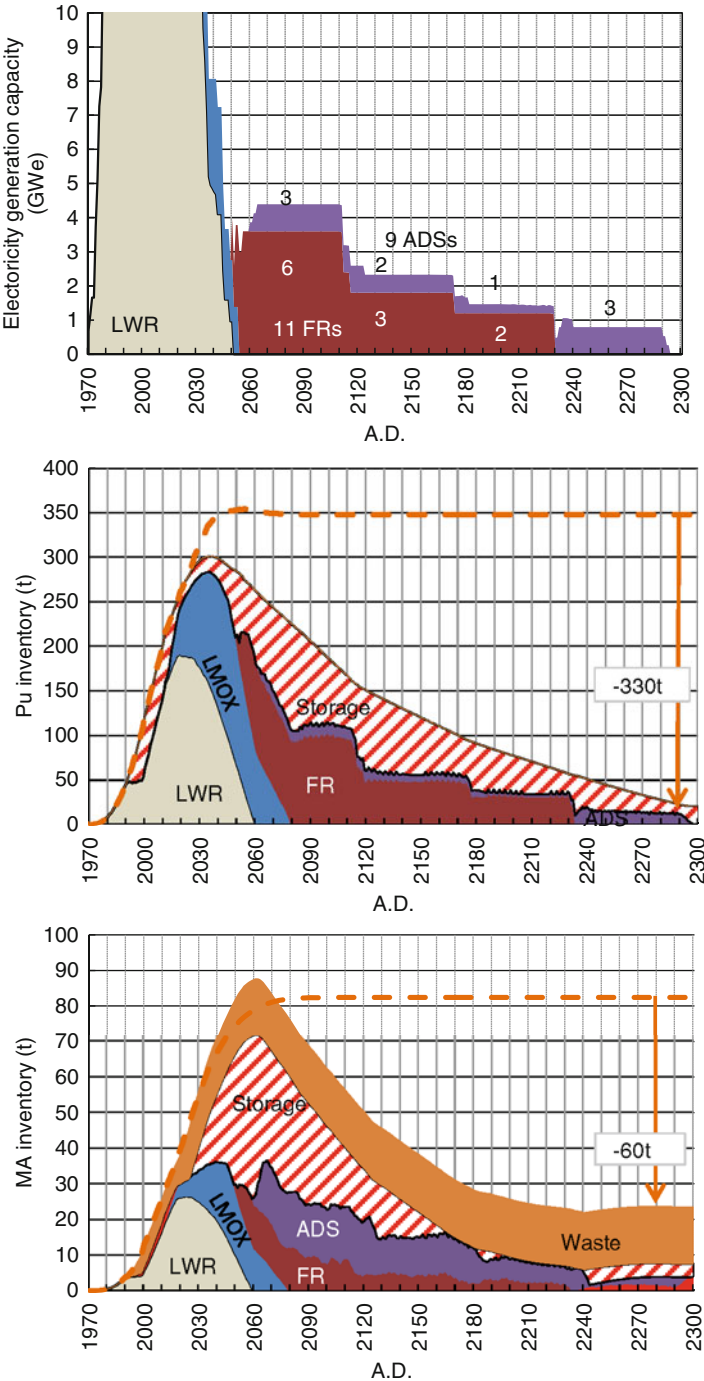


Fig. 19.9 Result of FR+ADS scenario

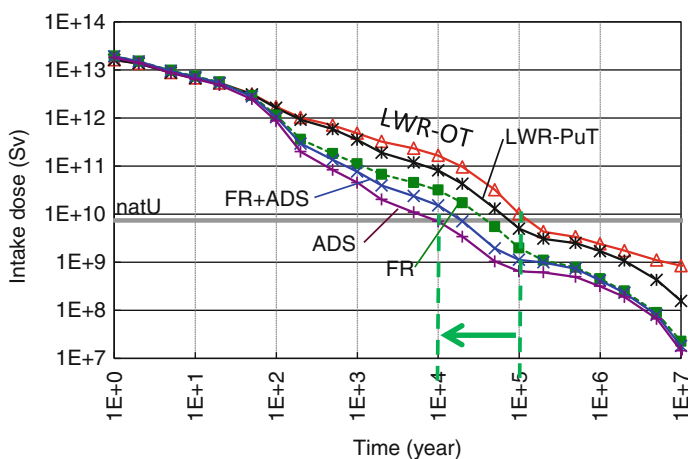


Fig. 19.10 Potential radiotoxicity of all wastes and uranium ore

waste corresponding to 40-year operation of the RRP, because the spent fuel assembly occupies more area and heat generation from the Pu in it also contributes.

In the LWR-PuT scenario, two kinds of waste form are produced: 37,000 glass waste forms containing FP and MA, and spent fuel assembly of MOX of 4,000 t. Each occupies 1.6 km^2 , and the total is 3.3 km^2 . Although an amount of MOX spent fuel is smaller than that of UO_2 spent fuel in the LWR-OT scenario by a factor of 11, it contains more heat-generating actinides such as Am and Pu, and its footprint is significant.

In the early several hundreds of years, ^{90}Sr and ^{137}Cs , whose half-life is around 30 years, are dominant for the footprint. They are separated in the RRP after 2025 as well as MA in the transmutation scenarios. They are absorbed by adsorbents such as zeolite and calcined to the waste form. Because half-life is rather short and the repository footprint is almost proportional to heat generation, long-term storage of the calcined waste is effective [9]. After 300 years of storage, an accumulated layout for the TRU wastes that is low heat generating and with long-term radioactive wastes becomes available. The footprint of this layout is smaller by two orders of magnitude than a typical layout for the vitrified waste. After separating ^{90}Sr and ^{137}Cs , ^{241}Am , whose half-life is 432.2 years, becomes dominant, but this nuclide is transmuted in the transmutation scenarios. Heat generation from other fission products that are vitrified quickly decays to the level of the TRU waste.

As result of the long-term storage and transmutation, the footprint becomes almost constant after 2025 (Fig. 19.11). The glass waste form that is produced before 2025 and contains MA occupies 0.5 km^2 . In the ADS scenario, partitioning and long-term storage of Sr and Cs in the wastes produced from reprocessing of ADS spent fuel is not assumed because the impact is small. As a result, the footprint gradually increases to 0.8 km^2 . Technologically, separation is possible in the reprocessing for ADS, and it will be applied if the increase becomes significant. Steps observed in 2230 and 2330 are caused by wastes of remaining TRU that will

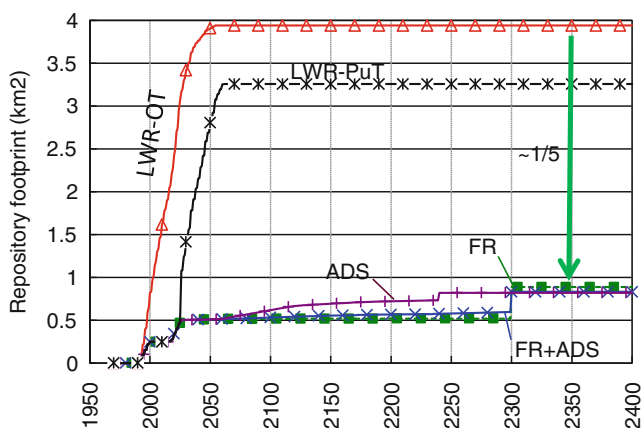


Fig. 19.11 Repository footprint when wastes are produced

be diluted to the glass waste, considering heat generation. The remaining TRU of the FR scenarios are more than that of the ADS scenario.

In the transmutation scenarios, the final footprint is around 0.8 km^2 , which is a fifth of the LWR-OT scenario. As is the case of radiotoxicity, the time of introducing partitioning is significant because more than half of the repository is occupied by glass waste forms with MA.

19.4.7 Discussion

Table 19.11 summarizes the results of scenario analysis. In comparison between LWR-OT and LWR-PuT, reductions are observed in Pu amount, repository footprint, and decay time of toxicity, although they are not drastic. Important benefits of MOX utilization are Pu isotopic deterioration as a nuclear weapon and improved confinement of radionuclides by calcinations, as discussed by Nishihara et al. [7]. However, there remains 110 t of separated Pu that can raise concerns about proliferation.

In comparison between conventional and transmutation scenarios, significant reductions of TRU amount, repository area, and decay time of toxicity are observed. The remaining Pu undergoes several irradiations in the transmuter and is highly resistant to weapon utilization. Repository area is about one fifth and decay time is reduced by one tenth in the maximum case. To achieve such benefit, a total of 15–32 transmuters have to be introduced for 180–240 years with corresponding reprocessing and fabrication facilities. Cost and risk during operation of these facilities would be high compared to their reduction in the repository in the further future.

Comparing the transmutation scenarios, the number of units in the FR scenario is fewest owing to its high thermal output. However, transmutation performance is

Table 19.11 Summary of scenario analysis

Scenario		Transmuter		Period (years) ^a	Remaining Pu	Remaining MA	Repository	
		FR	ADS				Area (km ²)	Toxicity (years) ^b
Conventional	LWR-OT	–	–	–	350	80	3.9	100,000
	LWR-PuT	–	–	–	260	100	3.3	70,000
Transmutation	FR	15	–	240	40	17/16 ^c	0.9	40,000
	ADS	–	32	180	8	3/16 ^c	0.8	10,000
	FR+ADS	11	9	240	20	8/16 ^c	0.8	20,000

^aNecessary period for transmutation after closing LWRs
^bTime to decay less than toxicity of corresponding uranium ore
^cSeparated MA/vitrified MA

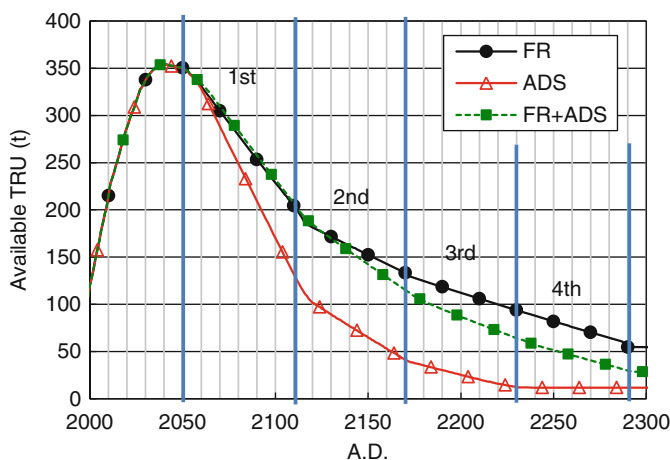


Fig. 19.12 Trans-uranium (TRU) amount available for transmutation in transmutation scenarios excluding minor actinides (MA) vitrified in waste

less than the ADS, resulting in longer transmutation era and larger remaining TRU. Figure 19.12 shows amounts of TRU excluding vitrified MA. An amount of the ADS scenario is reduced to 125 t after the first generation of the transmutation era from 2050 to 2110. In the FBR scenario, equal decrement is achieved after the second generation. Very high MA content up to 15 % in the FR fuel is also problematic. The decrement of the FR+ADS scenario is as same as that of the FR scenario until the second generation, but after that the decrement becomes faster because of ADS introduction.

Although transmutation performance of the FR is inferior to the ADS, cost including profit of electricity generation by transmuter would be much smaller than the ADS because the number of ADSs is doubled, accelerator cost is added, and thermal efficiency of the ADS is worse. Considering high MA content in the FR scenario, the FR+ADS scenario can be a modest solution, although the ADS scenario is preferable if rapid transmutation is required regardless of the cost.

19.5 Conclusion

With consideration of the phase-out option from NP utilization in Japan, an ADS for Pu transmutation was designed and scenario analysis introducing it was performed. The ADS was designed based on the existing design of the ADS for MA transmutation considering two options of Pu supply: pure Pu and a mixture of the same amount of Pu and U from the reprocessing plant for the LWR. After designing a one-batch core with large criticality drop, a six-batch core with a short operation day was analyzed. The criticality drop of the six-batch core was small enough in the equilibrium state. Several maintenance cases were assumed, and

those effects on the transmutation half-life were surveyed. Finally, a core with pure Pu supply and 30-day fuel reloading was selected as the reference case for the scenario analysis. The transmutation half-life was estimated as 24.8 years, meaning that the amount of Pu is reduced to half after 24.8 years of operation, taking maintenance and cooling time of spent fuel into account.

In the scenario analysis, once-through scenario of LWR spent fuel was referred to as a conventional scenario. LWR-MOX utilization with reprocessing of LWR spent fuel was also considered. As the transmutation scenario, three cases of transmuters that are only-FR, only-ADS, and both-FR+ADS were analyzed. The numbers of necessary transmuters were obtained as 15 to 32 units, and the necessary period for transmutation as 180–240 years. Benefit to the repository by reduction of Pu and MA was reduction of repository area by a factor of five and of decay time of toxicity by one order of magnitude. It was shown that MA vitrified in the LWR reprocessing plant before introduction of the partitioning technology in 2025 considerably deteriorates both benefit. Therefore, early introduction of the partitioning process and retrievability of MA from vitrified waste should be investigated.

In comparison among transmutation scenarios, reduction of TRU in the ADS scenario is two times faster than that in the FR scenario. It was found that MA content in FR fuel in the FR scenario was 15 %, which is much higher than the design limit of 5 %. On the other hand, the cost of the FR scenario including profit of electricity generation by transmuter would be much smaller than that of the ADS scenario because the number of ADSs is double, the accelerator cost is added, and thermal efficiency of the ADS is worse. Considering high MA content in the FR scenario, the FR+ADS scenario can be a modest solution, although the ADS scenario is preferable if rapid transmutation is required regardless of cost.

The present scenario study revealed that the number of the transmuters and time necessary to transmute Pu and MA in the LWR legacy is considerably large. However, impact on the TRU amount in the repository related to the nonproliferation issue, repository size, and decay time of the potential radiotoxicity is also expected to be large. Assessments of increasing cost and risk to operate transmuters based on the present analysis are the next subject.

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Nomenclature

w	Amount of heavy metal (t)
w_{tr}	Transmutation amount (t)
w_i	Initial amount (t)
P	Core thermal power (MW)
$h = \frac{P}{w_i}$	Specific heat (MW/t)

T_i	In-core period (year)
T_o	Out-core period (year)
ε_o	Operation efficiency
$\varepsilon_c = \frac{T_i}{T_i + T_o}$	Cycle efficiency
$E_{\text{fiss}} = 205 \text{ MeV} = 3.28 \cdot 10^{-11}$	Energy release per fission (J)
$N_A = 6.022 \cdot 10^{23}$	Avogadro number
\bar{A}	240 = averaged mass number
a	Constant (t/MW/year)
t	Time (year)
λ_{tr}	Effective transmutation rate (/year)
T_{tr}	Transmutation half-life (year)

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